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Sustainable Scientists

Improved energy efficiency could free up some of the $10 billion spent each year to power the U.S. scientific enterprise, while putting a dent in greenhouse-gas emissions.

Evan Mills[1]

Scientists are front and center in quantifying and solving environmental problems. Yet, as a spate of recent news articles in scientific journals point out, much can be done to enhance sustainability *within* the scientific enterprise itself, particularly by trimming the energy use associated with research facilities and the equipment therein *(i,ii,iii,iv)*.

Sponsors of research unwittingly spend on the order of $10 billion each year on energy in the U.S. alone, and the underlying inefficiencies drain funds from the research enterprise while causing 80 MT CO_2-equivalent greenhouse-gas emissions (see Box). These are significant sums considering the opportunity costs in terms of the amount of additional research that could be funded and emissions that could be reduced if the underlying energy was used more efficiently. By following commercially proven best practices in facility design and operation, scientists—and the sponsors of science—can cost-effectively halve these costs, while doing their part to put society on a low-carbon diet.

Improving energy productivity is a doubly worthy challenge, given that those making the biggest contributions to the science of sustainability often do so in highly energy-intensive facilities such as laboratories, computing centers, and hyper-clean environments. However, there is a long way to go. According to a UK Department for Environment, Food and Rural Affairs survey, while virtually all scientists viewed science and technology as an important factor in developing sustainable solutions, only 40% reported always or often considered the effect their work would have on the environment when planning their own research (*1*), and it has been estimated that only 1% to 3% of labs are designed "green" today *(4)*.

Given that today's scientific facilities can be more than 100-times more energy-intensive (measured in terms of energy use per unit of floor area) than conventional buildings (Figure 1), energy use is probably the single most important contributor to their overall environmental footprint *(v,vi,vii,viii)*. Particularly high energy intensities can be found in extreme climates, and hot and humid areas in the developing world are seeing strong growth in these types of facilities. A recent gathering in India highlighted the particular issues and opportunities there, and has resulted in the initiation of new activities focused on training and diffusing best practices (*ix*).

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Improvements in efficiency are increasingly being driven by interest in saving money and lessening environmental impacts. Various mandates are also spurring improvements. Examples in the United States include local building codes affecting privately-owned facilities and mandatory national targets for government-operated facilities stipulated by a series of Executive Orders, coupled with incentives and training as called for in the Energy Policy Act of 1992.

Box: Scoping Estimate of the $10 billion U.S. R&D Facility Energy Bill

There is no official estimate of energy-use in research facilities. National surveys such as those conducted by DOE (*x*) do not break these facilities out into a separate category. Here we present a rough scoping estimate for private- and public-sector research facilities in the United States based on available information, and current commercial-sector average energy prices of $0.098/kWh for electricity and $13/GJ for fuel. Given the magnitude of the result, a more detailed analysis is clearly warranted and would presumably be of strategic value to those funding the R&D enterprise as well as individual scientists trying to accomplish the maximum amount of work within a constrained budget.

Laboratories: Prior work indicates an expenditure of $4.2 billion per year for U.S. laboratory fume hoods as of 2004, based on bottom-up modeling (*6*), or $5.8 billion to reflect present-day energy prices. This is combined with $2.4 billion for lab plug loads and lighting per the end-use breakdowns from the EPA/DOE Laboratories for the 21st Century benchmarking database, which indicate that 29% of total lab energy is attributable to these end uses (*xi*).

Computing: A detailed estimate indicates total electricity consumption for U.S. servers and data centers at 61 billion kilowatt-hours as of 2006 *(8)*, including energy used directly by the IT equipment and associated space-conditioning systems. This translates to $5.9 billion at today's energy prices. The portion attributable to the research applications is $1.2 billion, based on a stipulated 20% fraction.

Clean environments: In the absence of any prior estimates, we refer to the estimated ratio of cleanroom to laboratory-type facility energy for California *(7)*, and scale this value to the U.S., for an estimate of $8.1 billion per year for all cleanrooms. The portion attributable to research applications is $1.6 billion, based on a stipulated 20% fraction.

The sum of these estimates is $11 billion, which, given the uncertainties, forms the basis of our conclusion that energy-use for high-tech research facilities in the United States is on the order of $10 billion. Assuming a national-average emissions factor of 0.959 kg CO_2-equivalent per kilowatt-hour, this corresponds to approximately 80 million tonnes of CO_2-equivalent emissions each year. Due to the absence of data, this does *not* include transportation energy use associated with research facilities (or related travel) or the energy associated with energy use of specialized facilities such as particle accelerators, electron microscopes, medical equipment, or transportation energy associated with research. Some of this is probably captured in the energy expenditures in "Energy-intensive" federal facilities, which was estimated at $0.9 billion in 2005 (*xii*).

Inefficiencies Exact a High Opportunity Cost for the Scientific Enterprise

Energy costs in research facilities can be staggering, e.g., electricity demand at the CERN site is 230 MW, or 800,000 MWh each year, worth about $80 million *(xiii)*. High-performance computing centers throughout the U.S. Department of Energy (DOE) system incur aggregate energy costs on the order of $100 million per year, a number that is rising rapidly with increasing demands for computing power. Oak Ridge National Lab is looking at scenarios of nearly 70 megawatts in power demand for new scientific computing facilities and associated cooling infrastructure within the next few years, corresponding to about $30 million per year in electricity costs for that one site alone *(xiv)*. Other supercomputers on the drawing board will demand well over 100 MW each. For comparison, a large central-station electric power plant produces 500 MW of power.

The good news is that the potential to trim these costs is dramatic. Energy savings in high-tech facilities on the order of 50% are readily achieved *(xv)* through an integrated effort on the part of those who fund the construction and operation of scientific facilities, researchers who occupy those facilities, and the architects and engineers who design and build them. Between 1977 and 1994, $47 million was invested in energy studies and $290 million in 1,100 retrofit projects at DOE facilities across the United States, with an average payback time of 3 years *(xvi)*. This yielded annual savings of $100 million and a return on investment in excess of 25%. Through these efforts, DOE cost-effectively reduced its nationwide facility energy intensity by 43%. Those efforts have continued. In 2008 alone, new projects were initiated at four DOE national laboratory sites with projected combined savings of $13 million per year (*xvii*).

Lawrence Berkeley National Laboratory's recently constructed Molecular Foundry (which contains laboratory, computing, and cleanroom spaces) provides an example in which substantial savings were achieved compared to typical practice, and with no net increase in construction costs (Figure 2) *(xviii)*. In the case of retrofitting existing buildings, there are usually net costs, but the investments are quite cost-effective. For example, energy upgrades at 36 computing facilities around the U.S. yielded a median payback time of three years *(15)*. Many measures, particularly those associated with improved operations and maintenance pay for themselves in a matter of weeks or months.

Improving Productivity and Safety Through Increased Energy Efficiency

"Doing the right thing" isn't the only reasons to strive for improved sustainability. The scientific enterprise depends on availability of ample energy and can be fettered by its cost. In the 1980s, LBNL's particle accelerators were responsible for the vast majority of site-wide energy use. Indeed, the Bevatron's energy budget only allowed for ten months of experiments each year. At the time, raising the energy-efficiency of the process (e.g., through improved magnets and power supplies) trimmed consumption and costs sufficiently to allow for a full year of experiments to be conducted.

In another example of how energy inefficiency can be a constraint to the conduct of research, as fume hoods are added to labs these facilities become starved for air once the aggregate flow exceeds the design capacity. Many labs could support more hoods—and thus generate more research output—if energy efficiency is improved in ways that safely reduce the flow and associated fan energy. Similarly, computing facilities are increasingly vexed by insufficient power infrastructure or excessive heat production, both of which can put *de facto* limits on compute capacity and jeopardize reliability *(xix)*.

Enhanced energy efficiency can also be a friend of safety, rather than compromising it as folk wisdom often implies. For example, by maintaining a relatively constant velocity of airflow into the hood opening, variable-air-volume (VAV) fume hoods dramatically lower energy use while reducing turbulence and thereby enhancing hood containment. VAV controls generally incorporate monitoring and alarming functions that also improve safety.

The Power of a Systems Perspective in Design and Operation

The potential for energy savings is routinely affirmed by benchmarking investigations that reveal energy intensity variations of a factor of five or more for facilities supporting similar activities and providing similar or greater levels of services, reliability, comfort, and safety *(15)* (Figure 1).

Particularly significant gains – and savings in up-front construction as well as ongoing operating costs – can be achieved by optimizing high-tech facilities at the systems level, as opposed to focusing only on individual pieces of equipment. The combined effect of multiplicative inefficiencies is well demonstrated in the case of data centers. As shown in Figure 3, overall system efficiencies range from 12% for poor practice to 60% for best practices. Beyond the effect of component efficiencies, over-estimates of process loads, redundant and uncoordinated "safety margins", and un-optimized control equipment and algorithms all conspire to produce facilities that use more energy than necessary.

Fully involving owners, occupants, and service providers in the articulation of "design intent" (*xx*) and establishing performance goals and metrics improves the likelihood of a successful outcome. A focused operations and maintenance program helps ensure performance over time.

One pervasive problem—dependency on rules of thumb—routinely leads to overestimation of energy needs *(xxi)*, resulting in wasteful capital expenditures for oversized cooling systems and ongoing expenses for inefficient operations. Unnecessary simultaneous heating and cooling is also commonplace and can be cost-effectively remedied. Selecting premium efficiency equipment—be it lighting, computers, fume hoods, refrigeration, or process devices—is as important for energy-cost savings as improving air-movement and space-conditioning infrastructure. Efficient process equipment imposes smaller loads on central space-conditioning systems, but this benefit is often overlooked by infrastructure designers.

Better facility management and rethinking the underlying processes can also yield considerable savings. According to a study by the American Chemical Society Green

Chemistry Institute, colleges and universities are looking at ways to adjust their curriculum so as to require fewer hoods (*xxii*). They found that the University of Oregon saved $250,000 in one-time capital costs for fume hoods and $87,000 annually in associated energy use by implementing a “greener” chemistry curriculum (e.g. reducing use of VOCs) that included experiments not requiring fume hoods. St. Olaf College cut the number of hoods needed in a new facility by nearly half, and MIT has established a program that automatically records night-time sash positions and reports the information back to the research group.

Laboratories

As an indication of the efficiency opportunities in labs, detailed benchmarking results of actual labs show an eightfold variation in energy intensity *(15).* The main categories of energy-saving measures for labs include specifying premium-efficiency fume hoods and lab equipment,(*xxiii*) avoiding over-ventilation, minimizing pressure drop in the ventilation system, energy recovery, minimizing simultaneous heating and cooling, and properly sizing space-conditioning equipment to match actual loads.

The dominant users of energy in labs are fume hoods, or other ventilation systems when fume hoods are not relied on as the primary source of air movement. A single average fume hood in the United States consumes approximately 35 MWh of electricity and 275 GJ of fuel ($8,000/year at typical prices), including direct ventilation energy and the energy associated with conditioning the air (*6*). Given more severe climates, the operating cost for the same hoods in Singapore or Fairbanks would be about $12,000/year (Figure 4). High-performance hoods can reduce these values by 75% (*6*).

While fume hoods represent the single greatest energy-saving opportunity in labs, the appropriate strategy is context-dependent (*xxiv*). For example, where hood density is low (and hoods are not the primary source of general lab ventilation), using bypass hoods rather than VAV hoods is simpler and just as efficient.

It is not enough to have a well-designed facility; occupants often must participate by activating energy-efficient features. For example, one study found a 66% savings potential for improved fume hood sash management *(xxv)*. The sash-management savings potential in MIT chemistry labs was estimated to be $350,000 per year. In addition, while infrastructure decisions (building envelope and ventilation) are typically not in the direct control of researchers, the specification and purchase of energy-efficient lab equipment is something they can influence.

Computing

As many forms of research move from the bench-top to the computer, high-performance computing is overtaking accelerators and other energy-intensive processes as the primary electric load at many research facilities. Computing energy-intensity has become so significant that the up-front capital cost of power and cooling infrastructure routinely exceeds that of the IT equipment itself *(xxvi)*. Due to increasingly demanding computing objectives—e.g. for achieving high-fidelity kilometer-scale climate simulations—energy requirements for the fastest next-generation facilities could rise sharply. As a proxy for this, computing power for high-resolution climate models is expected to increase on the order of 1000-fold from current levels (*xxvii*). A recent DOE report (*xxviii*) contemplates an exaflop (10^{18} flop) High-performance Computing system requiring over 130 MW of power, while the potential to achieve the same performance at high-efficiency could require as little as 20 MW. The business-as-usual scenario implies emissions of 700,000 tons of carbon-dioxide annually and an annual energy bill of $114 million for this single facility. These values represent energy used by the IT equipment only, i.e. excluding cooling, which could double these values if not provided efficiently. Other scientific computing applications will not likely present the need for such increases in computing power, but still have a large scope for improved efficiency.

The prodigious use of computing power translates into an untenable need for air-conditioning capacity. The energy and environmental price tag aside, a recent survey found that 42% of conventional data centers expect to run out of cooling capacity within one to two years (*xxix*). Benchmarking results for computing sites in the United States show that the fraction of total power going to computing itself ranges from 30% to 75%, a reflection of the inefficiencies of power and space-conditioning systems. LBNL's planned Computational Research and Theory (CRT) Facility is aiming for a target of 83% (implying a highly efficient cooling strategy). To put this in context, the entire LBNL Campus currently has a 13-megawatt electric demand, which would have nearly quadrupled with the initially proposed 35-megawatt CTR. The current goal is containing the ultimate size to 17 megawatts, corresponding to a $15 million annual reduction in energy costs.

The "Green500" list—an initial rough attempt at benchmarking the energy performance of supercomputers—ranks the world's top 500 sites by MFLOPS per watt of power *(xxx).* A variation of 1.5-fold is seen among the top 10 alone, and of 100-fold for the entire list. Some of the fastest machines on the list are also the most efficient. These are crude metrics, however, and improved analytics are needed in order to properly rate and rank supercomputing system energy performance.

Efficiency opportunities for computing facilities include improved IT equipment and its power supplies, uninterruptible power supplies, and more efficient cooling strategies (Figure 3). Computational efficiency can also be improved, and underutilized machines can be consolidated and virtualized. Fundamental process changes can also be implemented, such as shifting to direct-current infrastructure, which in one demonstration project yielded 10% facility-wide savings compared to the best-available AC configuration, and more than 25% compared to conventional practice *(xxxi)*. Pilot projects have already demonstrated this technology in the U.S., Germany, and Japan.

Deeper savings can be achieved with fundamental architecture changes reflected in current conceptual designs for low-power, application-driven semi-custom embedded processors (*xxxii*). If successful, energy savings for a single next-generation climate-modeling facility for a task such as 1.5km-resolution climate modeling would top $1 billion per year (*xxxiii*). Systems such as this, coupled with renewable power supplies, would go as far as to achieve full carbon neutrality.

Clean Environments

Clean environments are widely embedded in research facilities, ranging from biotechnology to optics to semiconductors *(xxxiv)*. With up to several hundred air-changes each hour, these are among the most energy-intensive of high-tech environments.

A comparison of eight ISO Class-5 cleanrooms in the United States found a nearly \$400,000 per year (eight-fold) variation in floor-area-normalized ventilation energy costs (ranging from \$25 to \$215/m^2-year), an indication of significant energy-efficiency opportunities (*15*).

In clean environments, priority should be placed on premium-efficiency air-movement equipment and design, as well as more efficient tools and process equipment. As in other high-tech facilities, process changes can also yield savings. For example, mini-environments can isolate the sensitive process in a small—and more easily controlled—clean space, which allows for relaxed particle-count limits (and thus air-movement costs) in the surrounding space and thus energy savings *(xxxv)*. Rules of thumb for design air-change rates may not be well-founded. Benchmarking analyses show a factor-of-six variation in actual air-change rates, ACH, among “identical” ISO Class-5 cleanrooms (100 to 600 ACH). Of the facilities benchmarked, half were operating below the lower range of typical practice (250 ACH) (*15*). Real-time particle counting can be used to modulate ventilation speeds, thereby managing energy demand *(xxxvi)*. Expanded-area filtering can save energy (by reducing pressure-drop) and trim waste and maintenance costs thanks to less frequent replacement.

Towards Best Practices

Scores of specific energy efficiency measures can be applied in research facilities. To provide context and coordination, an overall sustainable-science energy strategy can be structured as follows:

- Institute an enterprise-level energy management program, integrated with other functions (risk management, cost control, quality assurance, employee recognition).
- Involve all key stakeholders early in design process, keep the team focused on common goals, clarify and document the rationale for key design decisions supported by energy use and performance benchmarks.
- Apply life-cycle cost analysis to purchasing and decision-making, including non-energy benefits (e.g. reliability and environmental impacts).
- Avoid excessive/redundant “safety margins” by using right-sizing to trim first costs.

- Include integrated performance monitoring controls in the design and incorporate the information gained into operations and maintenance, and an ongoing process of opportunity assessment.
- Incorporate a comprehensive quality assurance process (often called "commissioning" or "retro-commissioning") into new construction and renovation to detect physical deficiencies that erode savings and/or performance and to provide facility operations staff and researchers with site-specific training.

The challenge is as much institutional as it is technical. As an illustration, of 27 University of California Santa Barbara labs offered an unsolicited no-cost assessment of their energy opportunities in 2007, only 4 accepted *(3).* There are often split incentives when the researchers who stand to use energy more efficiently do not make capital investment decisions or pay the bills. Few if any sponsors of research consider energy efficiency as a criterion in evaluating grant proposals or grantee financial management.

The ultimate agents of change are the scientists occupying research facilities. While scientists cannot optimize sustainability without institutional support, they can provide the catalyst and convene otherwise fragmented parties in the process (e.g. research sponsors, architects, and engineers), be it weighing in during the design of a new facility, selecting equipment, or retrofitting and operating an existing facility more optimally, sustainable facilities require sustainability-minded scientists.

Incentives and Other Deployment Initiatives

As facility designers and energy managers achieve relative mastery of "ordinary" energy-saving technologies for homes and businesses, energy-efficiency research and deployment initiatives are expanding their horizons to include "high-tech" scientific facilities and processes.

There are many resources and programs to assist motivated research institutions. Particularly notable public-sector initiatives are DOE's Industrial Technologies Program (ITP), EPA and DOE's Laboratories for the 21st Century initiative, the California Energy Commission's Public Interest Energy Research Program, and a variety of research projects sponsored by the New York State Energy Research and Development Authority.

Meanwhile, energy utilities are beginning to offer rebates and other financial incentives to help high-tech customers implement and fund energy-efficiency upgrades. For example, the Utility IT Energy Efficiency Coalition, led by Pacific Gas and Electric Company, is being formed to coordinate initiatives appropriate to computing.

Labs are participating in the Leadership in Energy and Environmental Design (LEED) program for rating energy efficiency and other sustainability features, and LEED-like protocols for labs have been developed and similar processes are being assessed for computing and clean environments. The National Renewable Energy Laboratory's Science and Technology Facility, and labs at UC Santa Barbara and UC Davis have received the highest LEED rating ("Platinum") while saving about $90,000 per year in energy costs, and significantly improving the working environment *(4).* LBNL's Molecular Foundry (Figure 1) received LEED's "Gold" rating.

Industry is also taking initiative. Information-technology manufacturers have formed the Green Grid alliance to address efficiency and sustainability issues *(xxxvii)*. This group is exploring energy efficiency opportunities in servers and data centers, including standards, measurement methods, and new processes and technologies. The Semiconductor Industry is also developing process equipment energy efficiency improvement programs *(xxxviii)* and their *Green Fab* initiative is modeled on the Labs21 and LEED programs *(xxxix)*.

By leveraging these initiatives, the sponsors of research – who ultimately pay the energy bills – could benefit from promoting energy efficiency improvements in the facilities where the work they fund is performed. One place to start would be to introduce energy efficiency criteria into the process of soliciting and evaluating research proposals. If capital expenditures are part of a proposal, funding recipients could be encouraged or even required to purchase premium-efficiency equipment and optimize their facilities for minimum life-cycle cost and reduced greenhouse-gas emissions.

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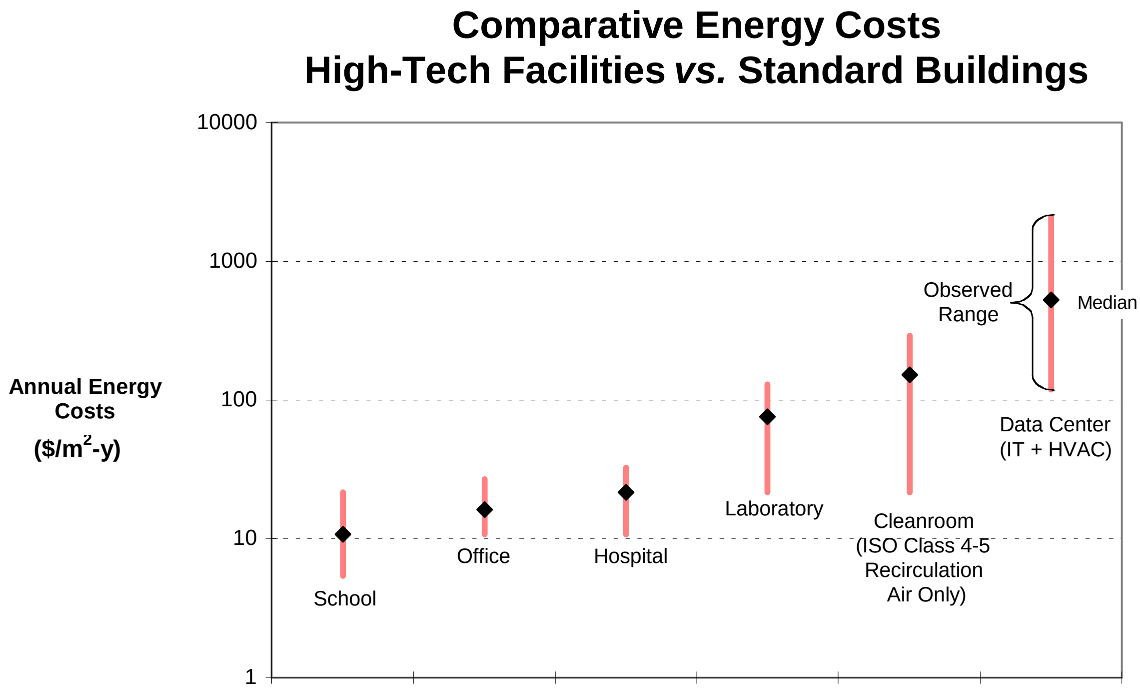

Figure 1. Range of measured energy intensities in high-tech facilities, with schools and offices shown for comparison. Adapted and updated from (*15*).

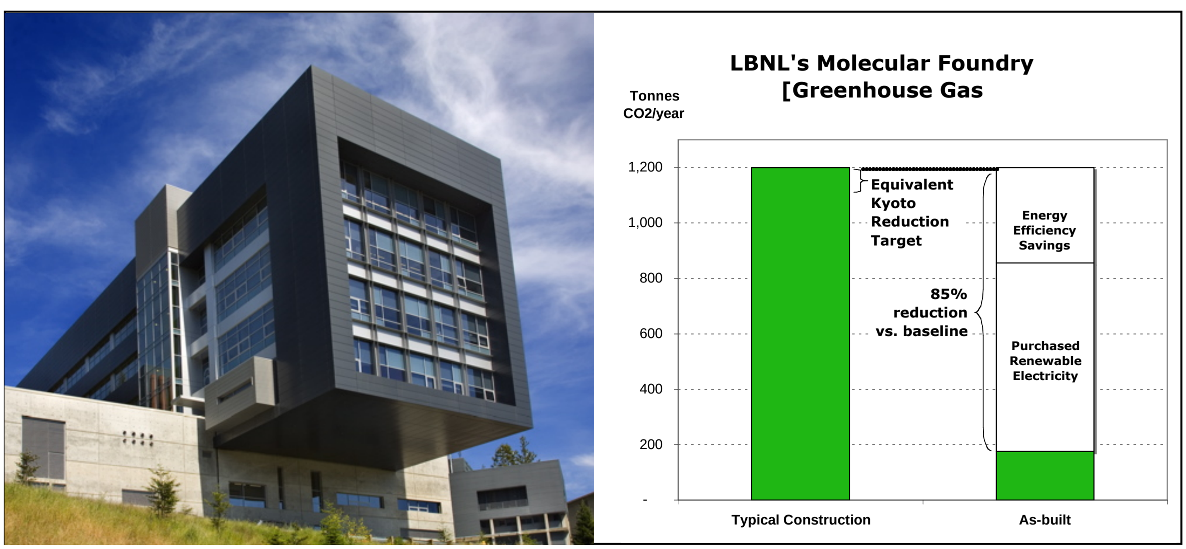

Figure 2. This nanotechnology research facility at Lawrence Berkeley National Laboratory (LBNL achieved a Leadership in Energy and Environmental Design (LEED) Gold Rating, thanks to extensive green and energy-efficient features, and renewable power purchases (*18*). Estimated carbon-dioxide emissions are 85% less than standard practice (which includes aggressive California building codes), vastly more than national average reductions called for by the Kyoto Protocol.

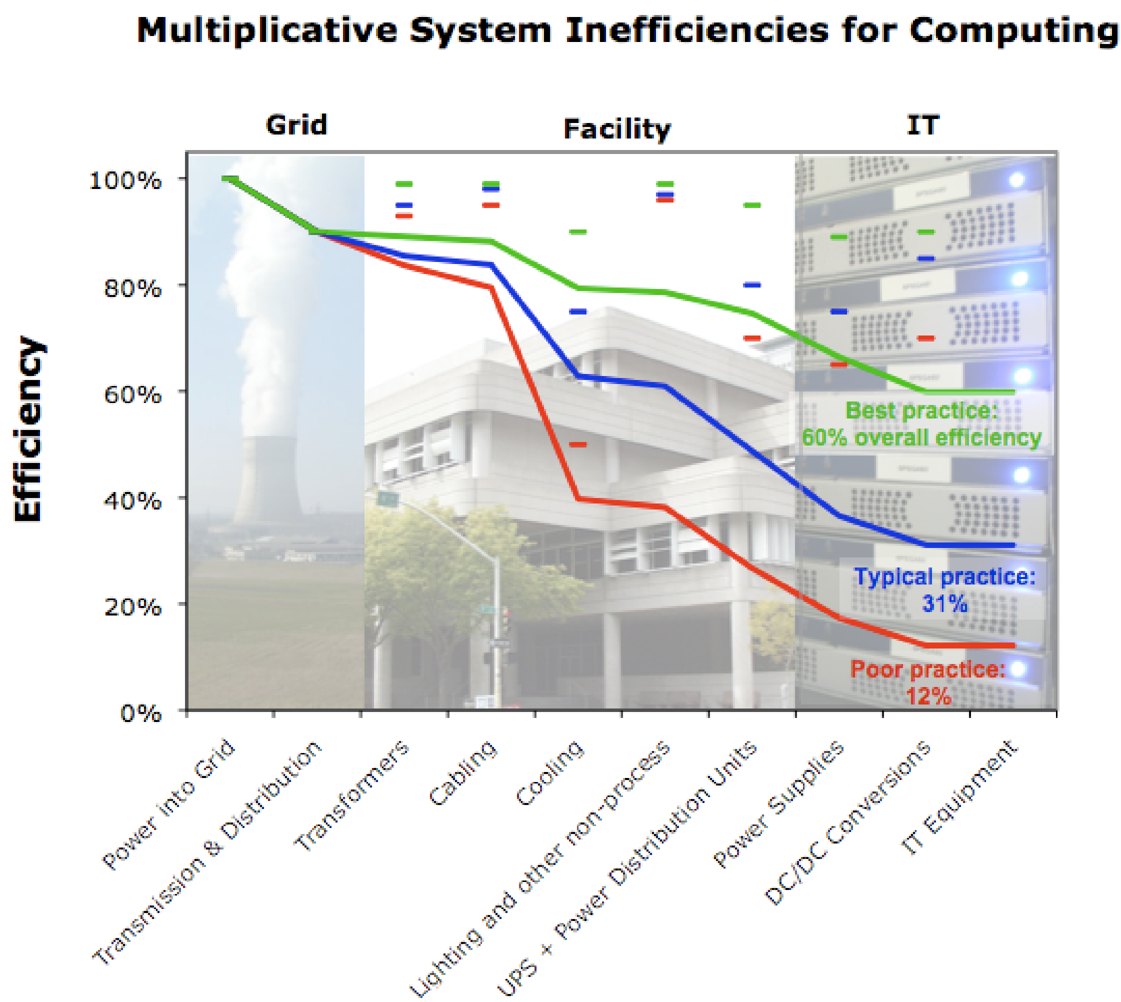

Figure 3. Individual (dashes) and cumulative (curves) efficiencies of data center systems. The system boundary shown here does not include "upstream" efficiencies in power generation, which are about 35%, or downstream losses and parasitic energy (e.g. fans) within the IT equipment itself.

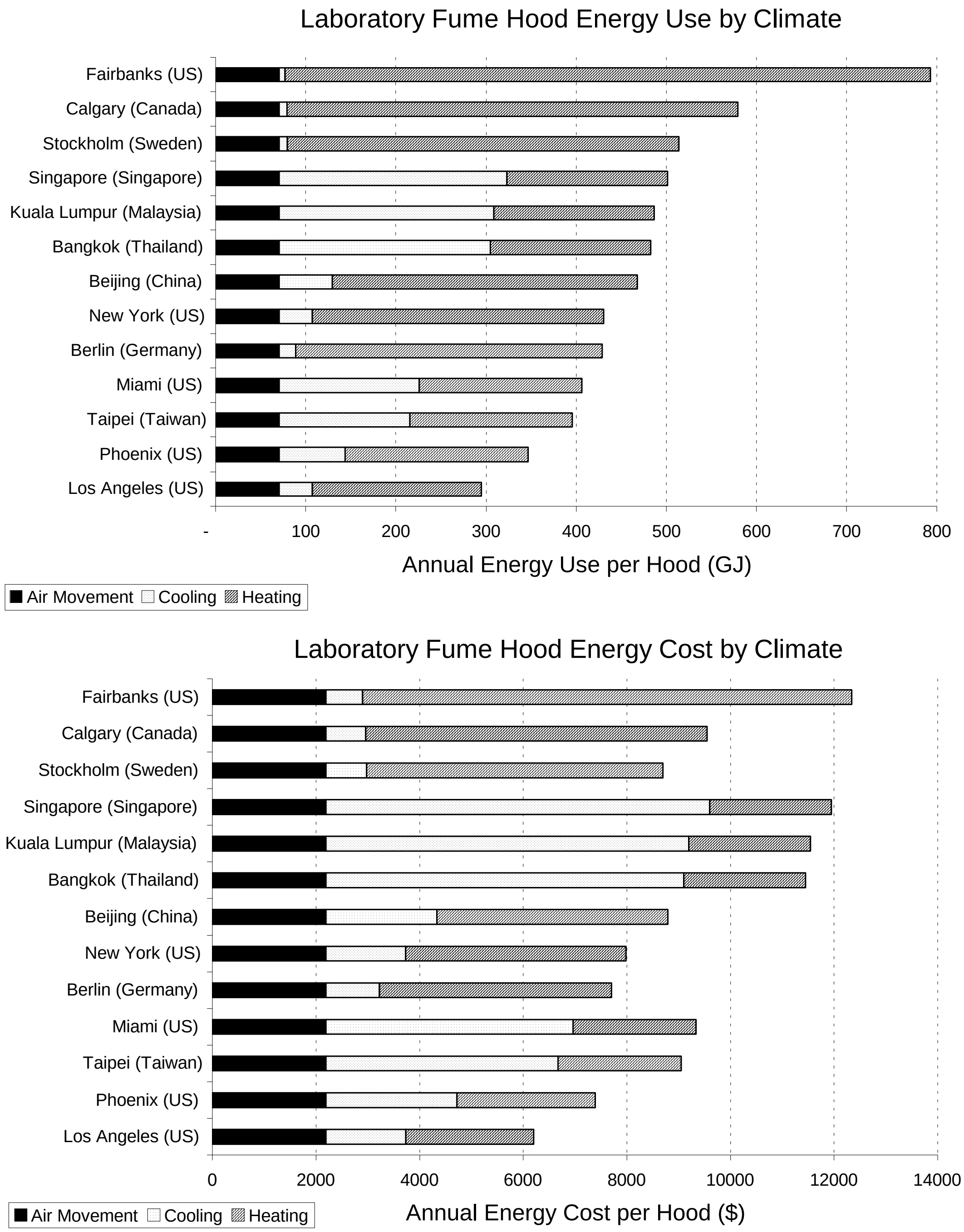

Figure 4. Energy use and operating costs for laboratory fume hoods in differing climates. Adapted from Mills and Sartor (*6*).

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